# PAH Emission from H II Regions in the SAGE-spec *Spitzer* Program

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**ABSTRACT**

Polycyclic aromatic hydrocarbons (PAHs) are some of the important components of the interstellar medium being both abundant and ubiquitous. We present the preliminary results on PAH emission in H II regions in the Large Magellanic Cloud using the spectroscopic data taken by Infrared Spectrograph (IRS; 5–38 $\mu$m), a part of the SAGE-Spec *Spitzer* Legacy program. The SAGE-Spec program provides the IRS mapping data of ten H II regions combining them with the archival data of 30 Dor. Among the eleven H II regions, an exemplary spectrum of an H II region (LHA 120-N 11: DEM L34) is presented. The integrated spectrum shows prominent PAH features at 6.2, 7 to 9, and 11.3 $\mu$m as well as a weak PAH feature at 12.7 $\mu$m. Several ionic lines such as [S IV] 10.51, [Ne II] 12. 81, and [Ne III] 15.56 $\mu$m, are also detected, which probe the ionization and/or density of the gas. PAH band ratios are examined over the region, and we investigate the correlation between the band ratios and the radiation field strength. Finally, we propose how the nature of PAHs and their correlation to the local environment can be extensively explored by *SPICA*.

## 1. INTRODUCTION

Polycyclic aromatic hydrocarbons (PAHs) are commonly considered to be the carriers of mid-infrared (MIR) emission bands that have been observed toward diverse objects (for a recent review, see Tielens 2008). PAHs are heated by UV photons and (re)emit rich spectral features mostly between 3 and 20 $\mu$m which are sensitive to local physical conditions. They have frequent interactions with ions, electrons, and other molecules as well as dust grains. Thus, PAHs play an important role on the energy balance and the ionization balance in the ISM, and it is important to understand the behavior of PAHs with given environment.

Madden et al. (2006) obtained infrared spectra of a number of galaxies with a wide range of metallicities using *Infrared Space Observatory*. The intensity of the PAH emission seen in these spectra shows strong dependence on metallicity of the host galaxies. In low-metallicity environments, very weak or no PAH emission is detected. In particular, it is unexpected to observe the paucity of PAH emission in some star-forming galaxies with low metallicities in the context that PAH emission is often used as an indicator of star formation. The effect of the metallicity-dependence of PAH emission has been examined in more detail. For example, Calzetti et al. (2007) derived 8 $\mu$m PAH emission luminosities of star-forming regions in nearby galaxies using the *Spitzer* IRAC 8 $\mu$m band and addressed the correlation between the PAH emission and the Pa$\alpha$ (1.8756 $\mu$m) emission line. They found the good correlation between them, especially for those with Galactic metallicity, but the relation shows deviations when lower-metallicity objects are included. This is likely to be due to the paucity of PAH emission in low metallicity.

Another important nature of PAHs is that the relative strength of different PAH emission bands vary significantly. Galliano et al. (2008) modeled PAH band ratios of various objects and found that there is a universal linear trend between the ratio of 7.7 $\mu$m band to 11.3 $\mu$m band and the ratio of 6.2 $\mu$m band to 11.3 $\mu$m band. Interestingly, the band ratios measured in spatially resolved regions of a galaxy vary as much as the range of the variety seen from various types of galaxies. This is an important aspect because if the physical conditions of a specific area are disentangled, observed PAH features can be interpreted accordingly. In fact, the band ratios are known to reflect the local physical conditions such as radiation field strength or gas density. Therefore, it is important to understand how PAH emission behave in different environments such as low metallicity environment by observing PAH emission in spatially resolved and well-characterized regions.

The Large Magellanic Cloud (LMC) is an ideal target since the LMC provides an opportunity to look at low metallicity environment ($\sim 0.5\ Z_\odot$) in close proximity (50 kpc). H II regions have plenty of UV photons to heat PAHs (but may destroy PAHs, too), so various PAH features have been observed frequently. Together with diagnostics of the physical conditions, H II regions in the LMC enable us to investigate PAH emission in detail.

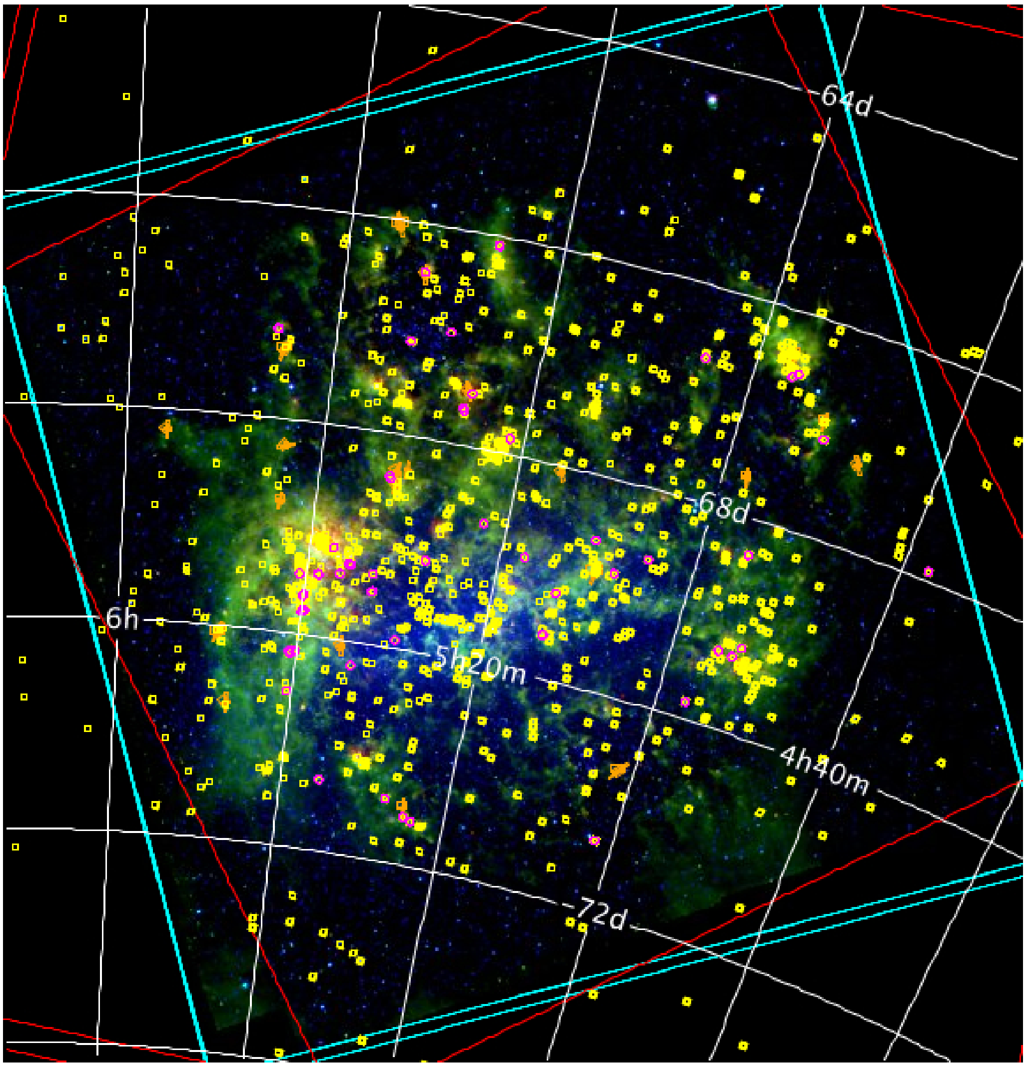


**Figure 1.** The 3 color composite image of the SAGE IRAC (3.6 and 8.0 $\mu$m) and MIPS (24 $\mu$m) images. SAGE IRAC mosaic coverage is shown in *cyan*, SAGE MIPS mosaic coverage is shown in *red*. Sources of SAGE-Spec are represented as overlays. SAGE-Spec IRS mapping spectral cubes are shown in *orange*, SAGE-Spec IRS staring mode spectra are shown in *yellow*, and SAGE-Spec MIPS-SED spectra are shown in *magenta*. The original figure is available at http://irsa.ipac.caltech.edu/data/SPITZER/SAGE/.

## 2. *SPITZER* SAGE-SPEC PROGRAM

Various surveys toward the LMC at a range of wavelengths have been carried out (e.g., HERITAGE; Meixner et al. 2010). As a *Spitzer* Legacy Program, there is a photometric survey in the infrared of the LMC, Surveying the Agents of Galaxy Evolution (SAGE-LMC; Meixner et al. 2006). Following the SAGE-LMC, SAGE-Spec (Kemper et al. 2010) is the spectroscopic survey of the LMC to examine the life cycle of dust and gas in the LMC. The *Spitzer* SAGE-Spec program consists of 224.6 hr of spectroscopic observations using *Spitzer* IRS (5–38 $\mu$m) and MIPS-SED (70–90 $\mu$m) observing modes to target 196 point sources as well as 20 extended regions, 10 H II regions and 10 atomic/molecular diffuse regions (Figure 1). In addition, the SAGE-Spec sample is extended by archival IRS staring mode observations as well as the archival IRS/MIPS-SED maps of the 30 Doradus H II region (Indebetouw et al. 2009) and two diffuse regions. In total, 11 H II regions and 12 diffuse regions are included in the SAGE-Spec (for more information on targets, see Table 6 in Kemper et al. 2010), and spectral maps of the 23 extended sources are obtained by IRS mapping mode and MIPS SED mode. All H II regions are mapped in strips that cover a width of 1′ and the length being the diameter of each H II region (the maximum length of the strip is limited to 5.4′). This mapping strategy allows us to examine the spatial variations of spectral features inside the H II regions.

## 3. PRELIMINARY RESULTS OF H II REGIONS

As a representative for the 11 H II regions, the integrated spectrum of one H II region (LHA 120-N 11; DEM L34) is shown in Figure 2. The spectrum shows prominent PAH features at 6.2, 7.7, 8.6, and 11.3 $\mu$m features and a weak 12.7 $\mu$m feature. Strong ionic lines such as [S IV] 10.51, [Ne II] 12.81, [Ne III] 15.56 $\mu$m are seen, which are diagnostics of the

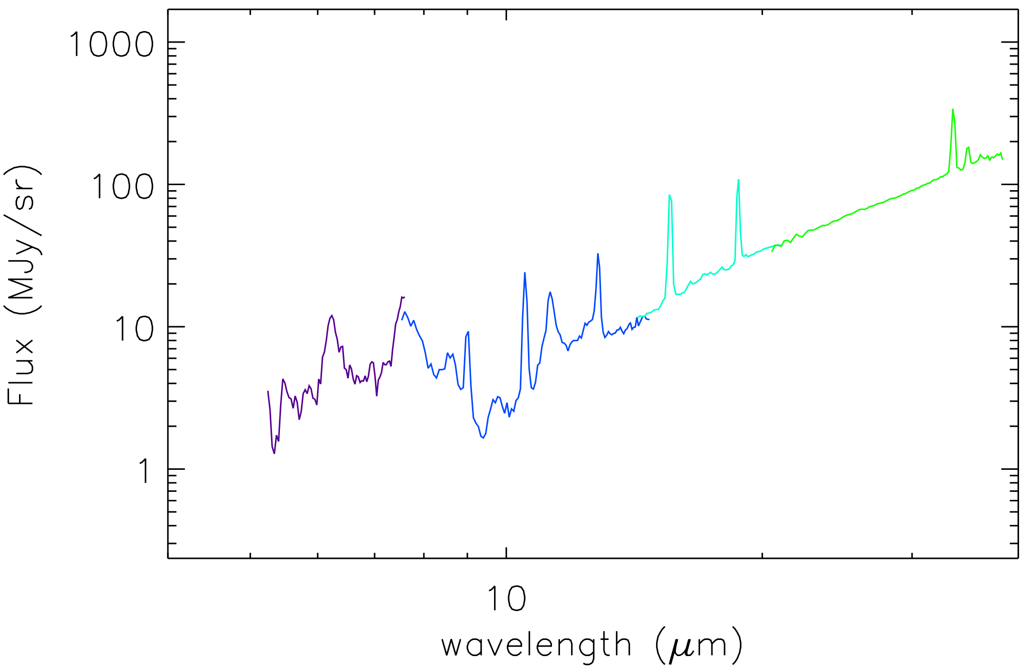


**Figure 2.** An exemplary integrated IRS spectrum of an H II region (LHA 120-N 11; DEM L34). Different colors indicate different orders of IRS; Short-Low 1st order (*blue*), Short-Low 2nd order (*violet*), Long-Low 1st order (*green*), Long-Low 2nd order (*cyan*).

physical conditions in the region. For example, the ratio of [S IV] 10.51 μm to [Ne II] 12.81 μm can be used as an indicator of radiation field strength similar to [Ne III] 15.56/[Ne III] 12.81 (Groves et al. 2008). This ratio is useful because both lines are observed by the same order (Short-Low 1st order: shown in *blue* in Figure 2), so deriving the ratio and examining their spatial distribution is straightforward. Beside the emission features, the dust continuum is dominant at longer wavelengths. While the integrated spectrum represents the IR emission features of the region, two-dimensional spectral maps provide the spatial distributions of emission features and the correlations between different features. PAH band ratios (e.g., $I_{6.2}/I_{11.3}$) are known to be sensitive to their charge state, which is physically related to the ionization/recombination ratio of the gas (e.g., Galliano et al. 2008). We compare the PAH band ratio map ($I_{7.7}/I_{11.3}$) to the line ratio map ([S IV]/[Ne II]). There seems to be a rough correlation between the PAH band ratios and the line ratios, but there are deviations from the correlation, too. This will be further discussed in Hony et al. (2013, in preparation).

## 4. PERSPECTIVE ON *SPICA*

*SPICA* (Space Infrared Telescope for Cosmology and Astrophysics; Nakagawa et al. 2011) is a next-generation infrared astronomy mission. Its cooled (< 6 K) large (3-m class) telescope will be able to offer superior sensitivity and high spatial resolution. One of the key instruments, the Mid-infrared Camera and Spectrometer (MCS) onboard *SPICA* will cover various PAH features. The MCS consists of three parts; the Wide Field Camera (WFC), the Mid Resolution Spectrograph (MRS), and the High Resolution Spectrograph (HRS). The MRS will perform integral-field unit (IFU) spectroscopy by image slicers providing a field of view of $12'' \times 8''$. It covers a wide wavelength range from 12.2 to 37.5 μm with a spectral resolution of $R$ ~1100–3000 and has good spatial resolutions (0.″32/pixel or 0.″44/pixel). These unique capabilities of the MRS will play a key role in studying spatial variations of PAH features, sub-features of PAH emission, and PAH emission in distant objects. Major PAH features are located at 3.3, 6.2, 7.7, 8.6, and 11.2 μm, and these features in distant galaxies (i.e., $z$ ~1–3) will be nicely covered by the MRS. PAH features have been detected in high-redshift galaxies, for example, Teplitz et al. (2007) observed two sources at $z = 1.09$ and $z = 2.69$ by *Spitzer*, both of which show prominent PAH features at 6.2, 7.7, and 8.6 μm. Using the MRS, the PAH features will be detected from more (fainter) objects at high-redshift and can be compared with the same features seen in local universe. In particular, the low metallicity environment in the LMC is representative for a typical low-mass galaxy at $z \approx 2$ (Panter et al. 2008), so we can study the variation such galaxies in a nearby analog in much more spatial detail.

Besides the features mentioned above, there are various PAH features at longer wavelengths, such as the 12.7 and 16.4 μm features and broad emission plateau from 15 to 19 μm. The reflection nebula NGC 7023 shows several PAH features in the high-resolution 15–20 μm spectrum obtained with the *Spitzer* IRS (Sellgren et al. 2007), which are likely to originate from large PAHs. It is noticeable that the 18.9 μm feature is locally distributed around the central heating source unlike other features seen in NGC 7023, and this indicates that it could be attributed to highly ionized PAHs. To examine these features in more detail, good spectral resolutions, high sensitivities together with efficient spectral mappings are required, which will be achieved by MRS.

In addition to the MRS, a WFC-SH grism ($R$ = 200) covering 4 to 13 $\mu$m will be useful to study PAH emission in the Milky Way, Magellanic Clouds, and nearby galaxies, and the MCS-WFC will provide morphologies of emission features in various MIR bands that can be compared with spectroscopic data. Finally, PAH studies will be strengthened by combining with capabilities of other instruments onboard *SPICA*; FPC-S (Focal Plane Camera-Science: 0.7–5 $\mu$m imaging and spectroscopy) to observe PAH emission at shorter wavelengths and SAFARI (SpicA FAR-infrared Instrument: 34–210 $\mu$m) to examine correlations between PAHs and warm/cold dust. It is expected that *SPICA* will open a new era for the research field related to PAH emission.

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